Reynolds-stress and triple-product models applied to a flow with rotation and curvature

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Introduction/Motivation

- Looking for Simple Rotational Flow Test Case
- Chow-Zilliac Wingtip Vortex: Grid Too Big
- Rotating Pipe Flow (Zaets[1992, 1994, 1996])
  - Simple Geometry
  - Simple Boundary Conditions
  - Extensive Experimental Interest
  - *Similar Physics*
  - More Challenging than Anticipated!

Lag Paradigm

- Lag Framework Utilizes Existing Equilibrium Models
- Explicitly Adds Equations to Model Non-Equilibrium Behavior

$$\frac{d\varphi}{ds} = \lambda\left(\varphi^{eq} - \varphi\right)$$

where:

$$\lambda = A_0\frac{\omega}{u} = \frac{1}{\mathcal{L}_L}$$

- ν_T-Lag Variable φ is Eddy Viscosity ν_T
- LagRST: Lagged Variables φ also include $R_{ij} = \overline{u_i' u_j'}$
- TTR: Lagged Variables φ also include $T_{ijk} = \overline{u_i' u_j' u_k'}$

Goal: Reliable Prediction Capability for Separated and Attached Flow

Lag Zeitgeist / TTR Model Change Required

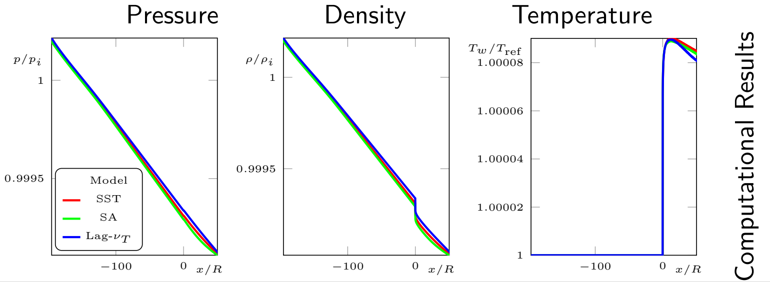
The Lag Zeitgeist

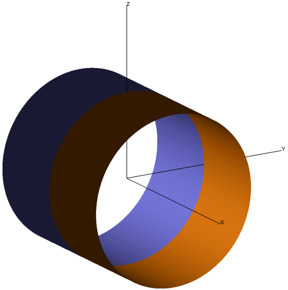
- Exact Terms (Just Say Yes)
- Numerical Stability (It's a Good Thing)
- History is Paramount (Convection is Exact)
- Do No Harm (Retain the Good)

TTR Model Change!

- Higher Spin Rotating Cases required $\sigma_k = 0.3$, (was $\sigma_k = 0.2$)
- Details of TTR Model in Paper
- Does not seem to make large differences on other flows reassessed so far

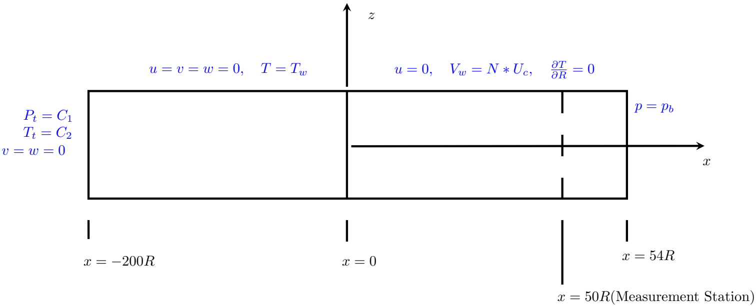
Experiment: Zaets Rotating Pipe Experiment





- $R = 0.03\,\mathrm{m}$
- $200R$ Stationary $\mapsto$ $50R$ Rotating
- $U_c = 10\,\mathrm{m/s}$ at Exit
- $288.15K \leq T \leq 291.15K$
- Atmospheric Pressure
- $V_w = 0.0, 1.5\,\mathrm{m/s}, 6\,\mathrm{m/s}$

Experiment: Zaets Rotating Pipe Experiment



- Hot Wires (Single, Cross, and Dissipation Sensors)
  1.2 mm$(= .025R)$ sensing elements
- Upstream/Inflow $200R$ Fully Developed Pipe $Re_\tau = 875$
- Spinning Section $50R$ Spinning Wall
- $V_w = 0.0, 1.5\,\mathrm{m/s}, 6\,\mathrm{m/s}$
- Experimental Data Utilized:
  - Axial Mean Velocity
  - Circumferential Mean Velocity
  - R_{11}, R_{22}, R_{33}

Computational Methodology -1

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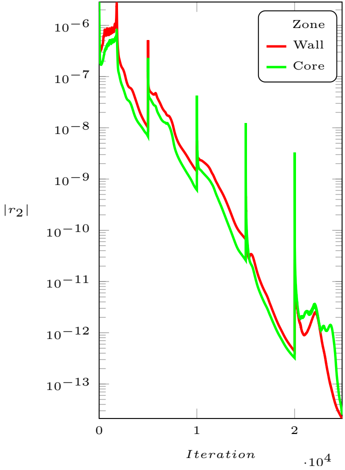
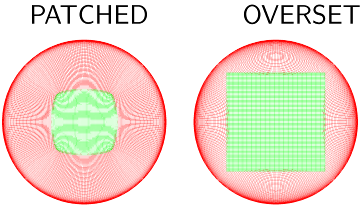




Solver: Overflow[modified] 2.2k
AIAA 2012-0444, AIAA 2013-2720

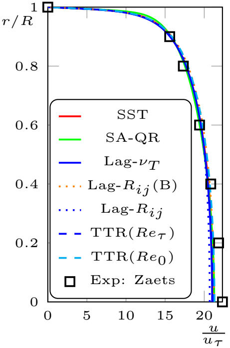
- 3D simulation
- Overset: Pegasus
- Matrix Dissipation or HLLC
- Multigrid / Grid Sequencing
- Low Mach Preconditioning

Computational Methodology -2

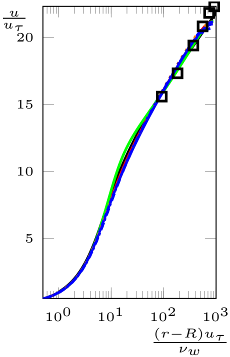
- Turbulence Modeling Test Case
  - Single Upstream (Fully Developed) State
  - Back Pressure Adjusted to Match $Re_\tau = 875$
  - Wall Spin Rate Constant Fraction of u_τ, not u_c
- Solution Convergence: Relatively Extreme
- Grid Sensitivity Results (More Radial, Less Axial)
- Grid System Overset or Patched Capable

Fully Developed Flow Region

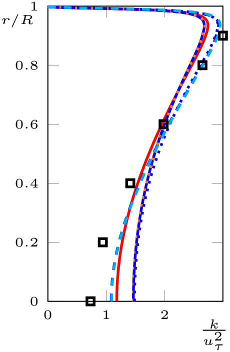
Axial Velocity (r/R)



Axial Velocity (u^+ vs y^+)

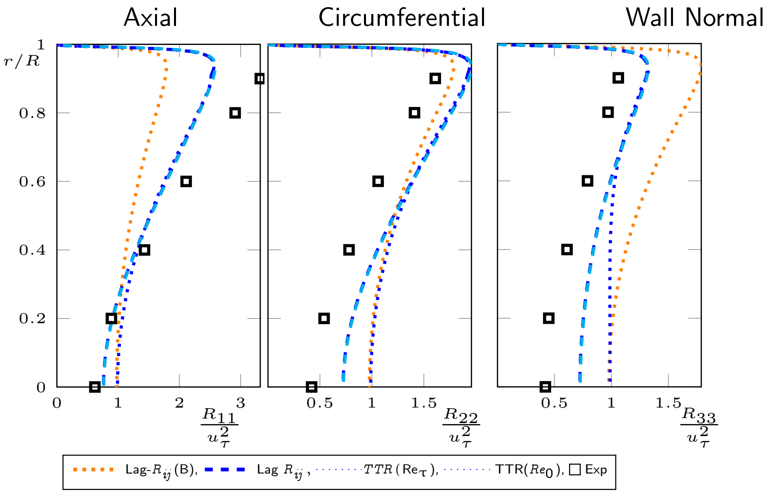


Turbulent Kinetic Energy



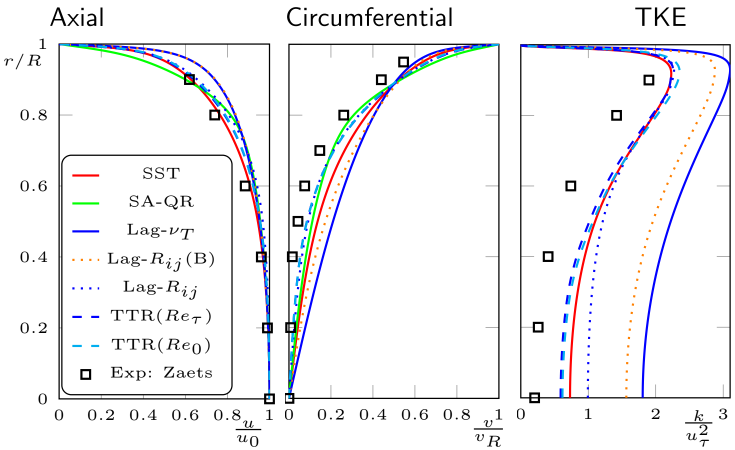
- General Agreement in Velocity Profiles
- TKE: TTR already Showing Improvements
- Relatively Low Re_τ Condition

Fully Developed Flow Region - Reynolds Stresses



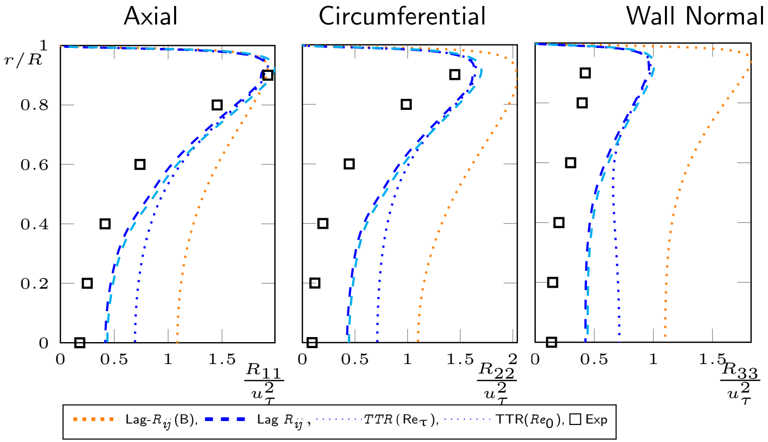
- Bousinesq $R_{ij}^{(eq)}$ Very Similar All Components
- Anisotropy of $R_{ij}^{(eq}$ Less Than Experiment
- TTR Model Affects Pipe Core, Smaller Effect in Wall Region

High Spin Rate ($x/R = 50$, $V_w/u_\tau = 13.\overline{8}$)



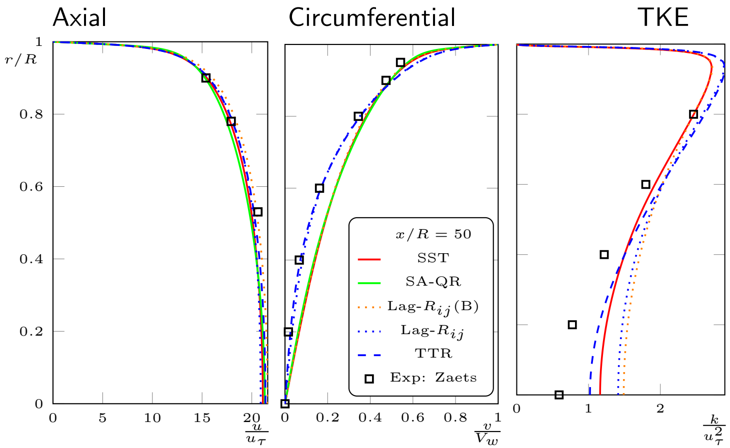
- More Scatter in Velocity Profiles (Than Fully Developed Region)
- Axial and Circumferential Velocity - Model Complexity Helps!
- TTR Improves Axis TKE Predictions
- Complex Models Have *not* been Rotation Corrected (yet)

High Spin - Reynolds Stresses



- Agreement *Looks* Better than Fully Developed Region
- Anisotropy of $R_{ij}^{(eq}$ Less Than Experiment
- TTR Model Affects Pipe Core, Smaller Effect in Wall Region

Low Spin Rate ($x/R = 50$, $V_w/u_\tau = 3.425\overline{8}$)



- Axial and Circumferential Velocity - Model Complexity Helps!
- Lower Spin Rate Improves Prediction -(No Rotation Corrections in R_{ij}, T_{ijk} yet)
- TTR Improves Axis TKE Predictions

Low Spin - Reynolds Stresses

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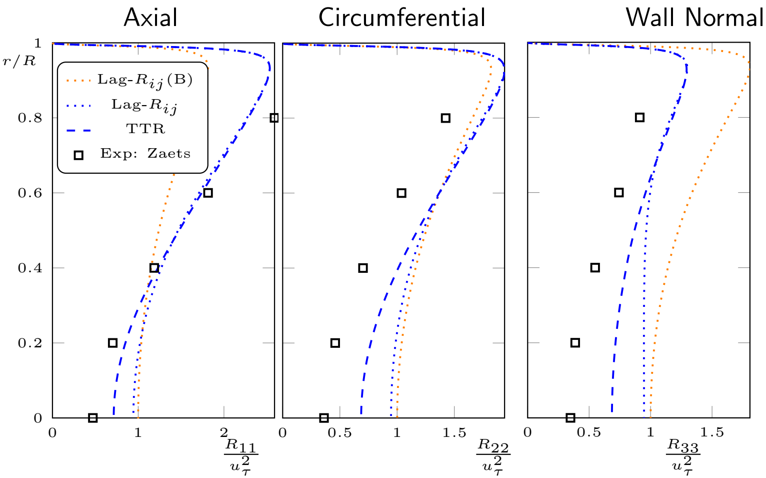
Introduction
Methodology
Experiment
Computational Methodology
Computational Methodology
Results
Fully Developed (Upstream Flow)
High Spin
Low Spin
Conclusions/Further Work



- Again, Agreement *Looks* Better than Fully Developed Region
- Anisotropy of $R_{ij}^{(eq}$ Less Than Experiment
- TTR Model Affects Pipe Core, Smaller Effect in Wall Region

Conclusions

- Much of the Turbulent Decay inherent in More Accurate Production of R_{ij}, T_{ijk} models
- TTR Model improves predictions where it should (pipe core)
- Wall Bounded Region TTR/R_{ij} models agree (as expected)
- SST did surprisingly well (variable c_μ?)
- TTR Model Required σ_k tweak - being assessed on other flows (not much affect so far)

Future Plans

- Rotational Corrections (much previous work to mine) will help (Spinning Cylinder)
- Anisotropy Fixes are in the pipeline